Elastic to plastic crossover below the peak effect in the vortex solid of $YBa_2Cu_3O_7$ single crystals

S. O. Valenzuela,[1,][*] B. Maiorov,[2] E. Osquiguil,[2] and V. Bekeris[1]

[1]*Laboratorio de Bajas Temperaturas, Departamento de Física, Universidad de Buenos Aires,*
Pabellón I, Ciudad Universitaria, 1428 Buenos Aires, Argentina
[2]*Centro Atómico Bariloche and Instituto Balseiro, Comisión Nacional de Energía Atómica,*
San Carlos de Bariloche, 8400 Río Negro, Argentina
(Dated: July 5, 2001)

We report on transport and ac susceptibility studies below the peak effect in twinned $YBa_2Cu_3O_7$ single crystals. We find that disorder generated at the peak effect can be partially inhibited by forcing vortices to move with an ac driving current. The vortex system can be additionally ordered below a well-defined temperature where elastic interactions between vortices overcome pinning-generated stress and a plastic to elastic crossover seems to occur. The combined effect of these two processes results in vortex structures with different mobilities that give place to history effects.

PACS numbers: 74.60. Ge, 74.60. Jg

The complexity of vortex dynamics in type II superconductors arises from the competing roles of vortex-vortex interactions promoting order in the vortex structure (VS) and random defects in the sample promoting disorder. Complex dynamical behavior of vortices has been usually accompanied by the phenomenon known as the "peak effect" (PE), which refers to a peak feature in the critical current density, J_c, as a function of temperature or magnetic field.[1,2,3,4,5,6,7,8,9] The PE has been observed below the upper critical field, $H_{c2}(T)$, in conventional superconductors[1,4,5,9] and just below the melting temperature,[8] T_m, in high T_c materials such as $YBa_2Cu_3O_7$ single crystals.[6,7] A qualitative explanation of the PE was proposed forty years ago by Pippard[2] who argued that J_c increases anomalously if the rigidity of the vortex lattice decreases faster than the pinning interaction as the normal state is approached. This idea was further developed by Larkin and Ovchinnikov.[3] Nevertheless, there are still fundamental questions regarding the underlying physics of this phenomenon, especially in relation with the appearance of topological defects in the VS at the PE and its connection with its dynamic response.

In this paper, we report on history effects in twinned $YBa_2Cu_3O_7$ crystals in the vicinity of the PE as observed in ac transport and ac susceptibility measurements. Vortex states with different degrees of mobility have been observed in both low,[4,5,9,10] and high T_c materials.[7,11,12,13] It has been frequently argued that the difference in the mobility reflects distinct degrees of topological order in the VS as it is driven through the random pinning potentials: in a disordered and defective VS the interaction with pinning centers would be more efficient than in a more ordered lattice because of a reduction of the effective shear modulus or of the correlation volume of the lattice.[4,9,12,13] In fact, changes in the degree of order of the VS have been directly observed with neutron scattering experiments when the VS is shaken with oscillating currents (or fields).[14]

Having these results in mind, our experimental observations suggest that ac currents flowing during the cooling of the sample through the PE (either injected in a transport experiment or induced in an ac susceptibility measurement) partially inhibit the disordering of the VS that normally occurs at the PE. As disorder heals, the VS is trapped in a more mobile state.

An additional contribution to the vortex lattice healing arises at low temperatures far from the PE where our results suggest that a plastic to elastic crossover occurs.[15] As the sample is cooled, the vortex lattice rigidity increases and, below a certain threshold temperature, the vortex-vortex interactions become more relevant relative to the pinning potentials. This further contributes in ordering the VS, which is in a more mobile state on warming and thereby hysteretical behavior is observed.

We will first refer to our transport data and next to our ac susceptibility results from which identical conclusions can be derived. Resistance measurements in crystal A[16] employed the standard four probe technique with contacts made with silver epoxy over evaporated gold pads (contact resistance below 1 Ω). The sample (dimensions 0.7 mm × 0.3 mm × 10 μm) has a sharp resistive zero field transition at 93.2 K and a transition width of 500 mK (10%-90% criterion). Twin boundaries (TB) observed with polarized light microscopy are distributed as indicated in the inset of Fig.1.

A sinusoidal ac current I_{ac} (peak) = 30 mA of frequency $f = 37$ Hz was applied in the $a - b$ plane of the sample, 45° away from the TB planes. The voltage signal was preamplified with a low noise transformer and its in phase value, $V(T)$, was measured with a lock-in amplifier as a function of temperature. We found that Joule dissipation at the current contacts drove the sample 1.4 K above the measured temperature. The temperature shift (assumed constant for our temperature window) occurs almost immediately after the measuring current is applied (*i.e*, at time scales well below our amplifier integrating time constant). This shift is straightforwardly determined by matching the *linear* normal state resistivity curves, $R(T)$, for $I_{ac} = 30$ mA with the $R(T)$ curves
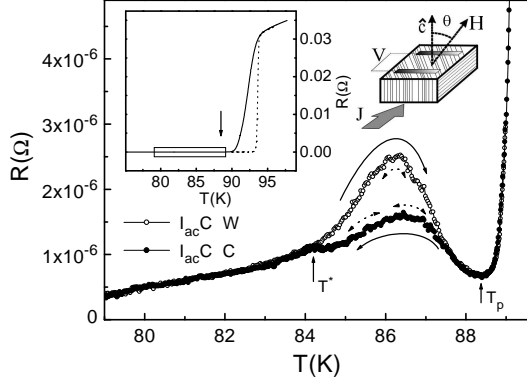
FIG. 1: Hysteretic transport measurements in a twinned YBCO single crystal (sample A) for H_{dc}=3 kOe, I_{ac}=30 mA and f=37 Hz. The inset shows the resistive transition in zero dc field (dotted line) and with H_{dc}=3 kOe (full line). The marked area is enlarged in the main panel. Full symbols were obtained in a dc-field and current cooling procedure (I_{ac}C C). Open symbols represent the warming curve (I_{ac}C W) measured immediately after obtaining the I_{ac}C C curve. Temperature was varied in the directions indicated by the arrows. The crossover temperature, T^*, and the peak temperature, T_p, are indicated by arrows (see text).

obtained with a much lower applied current for which heating is negligible. We have therefore added 1.4 K to our thermometer readings to plot our data as a function of the temperature of the sample.

In Fig. 1, left inset, we show the zero field transition in dotted line as compared to the transition in applied dc field shown in full line. The magnetic field $H_{dc} = 3$ kOe was applied at an angle $\theta = 20°$ from the crystallographic c axis, and its direction was chosen so that H_{dc} pointed out of all the twin planes to avoid the Bose-glass phase[12,17,18] (see inset in Fig 1). The main panel of Fig. 1 is an enlarged area of the transition shown in the upper inset, and it presents transport measurements that correspond to different thermomagnetic histories of the sample. Our measurements were performed by varying T in the direction indicated by the arrows at a rate of $\pm$ 0.3 K/min. Full symbols were obtained in a field and current cooling procedure (I_{ac}C C), *i.e.* the dc magnetic field and the ac current were applied in the normal state and the sample was then cooled. Empty symbols represent the warming curve (I_{ac}C W) obtained immediately after measuring the I_{ac}C C curve (full symbols).

When the temperature is increased, the resistance first increases, then starts decreasing and finally increases again. Since the resistance is related to the average vortex velocity, the dip in the resistance indicates a less mobile VS. This behavior signals an enhancement of pinning, and the dip in the resistance is accompanied by a peak in J_c identified as the PE.[6,9] The temperature where it happens, T_p, is indicated with an arrow. Above the PE, the critical current reduces to zero at the melting line.[18,19] The main results in Fig. 1 are that, below T_p,

we find a hysteretic behavior that is limited to a temperature interval around the peak in the resistance and that the response becomes reversible below a well defined temperature $T^* \sim 84.2$ K.

It has been shown that history effects observed in ac susceptibility in $YBa_2Cu_3O_7$ can be understood in terms of a dynamical reordering of the VS caused by the induced ac currents that shake the vortex system.[12,13] Moreover, the ac response changes in an approximately logarithmic way with the number of ac cycles.[13] In transport experiments, it is the applied ac current that forces vortices to move inside the sample and a dynamical reordering occurs. Non-saturated ordering as a possible explanation for the different vortex mobilities in the cooling and warming curves of Fig. 1 is discarded by the observation of reversible partial temperature cycles performed as indicated by dotted arrows in Fig. 1.[20] This result shows that the hysteretical behavior is related to a change in the character of the vortex lattice motion at T^*. This change, we believe, is determined by the relation between the pinning induced shear stress and the plastic limit of vortex motion associated with the vortex lattice shear modulus c_{66} (see for example Ref. 15). At low temperatures, well below the PE, the VS becomes more rigid and it enters an elastic regime where elastic interactions of the VS dominate over pinning. The enhanced elastic interaction enables the VS to be in a more mobile state on warming. Notice that at high temperatures, where elastic constants have dropped, the I_{ac}C C and I_{ac}C W cases coincide.

Following these results, there are two processes that may lead to the increase in the order and mobility of the VS: one process is related to the increase of the elastic constants over pinning at low temperatures whereas the second one is due to the vortex motion induced by the driving current (at all temperatures). Between T^* and T_p, the VS can contain a certain density of defects that the ac current appears not to be able to heal in our experimental time scales.

A question that arises is what consequences has cooling the sample through the PE without rearranging the VS (with a driving current). To answer this question, the sample was cooled from the normal state with applied dc field and with *zero applied current* down to a certain starting temperature, T_s, and then the warming curve was measured. This ZI_{ac}C W procedure was repeated reaching each time a different T_s. The results are plotted in full symbols in Fig. 2. For comparison, we also plot the I_{ac}C W results of Fig. 1 in open symbols. These are revealing results. The measured resistance follows different paths as a function of temperature if T_s is above a certain crossover value (~ 84.2 K). It should be noted that the sample has in fact been cooled 1.4 K below the temperature at which each ZI_{ac}C W curve in Fig. 2 seems to start (because of heating). For measurements that begin above the crossover temperature, the VS has less mobility and the highest measured ZI_{ac}C W dissipation level that corresponds to the lower starting
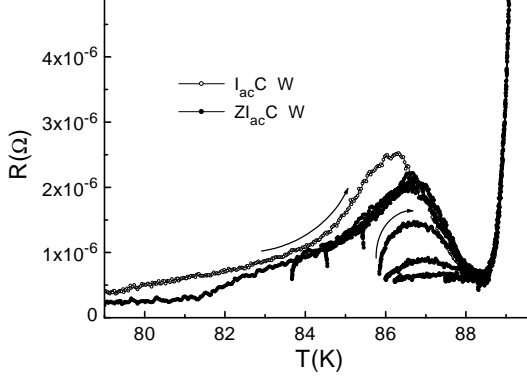
Fig. 2. S.O. Valenzuela

FIG. 2: Resistance *vs* temperature measurements obtained on warming after cooling to different starting temperatures, T_s, in zero current, ZI_{ac}C W (full symbols, sample A). $T_s = 69$, 82.2, 83.1, 84.1, 84.4, 84.6, 84.8 and 86.1 K. For comparison, it is shown the I_{ac}C W curve in open symbols (see Fig. 1). $H_{dc} = 3$ kOe.

Fig. 3. S.O. Valenzuela

FIG. 3: Hysteretic real ac susceptibility, $\chi'(T)$, in a twinned YBa$_2$Cu$_3$O$_7$ single crystal (sample B) for H_{dc}=3 kOe, h_{ac}=2 Oe and f=10.22 kHz. The inset shows the sharp zero field transition in dotted line and the hysteretic behavior for H_{dc}=3 kOe in full line. The marked area is enlarged in the main panel. Full symbols were obtained in a dc and ac field cooling procedure (F_{ac}C C). Open symbols represent the warming curve (F_{ac}C W) measured immediately after obtaining the F_{ac}C C curve. Temperature was varied in the directions indicated by the arrows. The crossover temperature T^* and the peak temperature, T_p, for this sample are indicated by arrows (see text).

temperature (< 70 K) is not reached. As the starting temperature increases towards the PE temperature, T_p, this becomes more evident. At high enough T_s's, the ac current is unable to move the lattice at levels that are comparable with, for example, those obtained through the I_{ac}C W procedure. In contrast, at temperatures below the crossover, the highest measured ZI_{ac}C W dissipation level is reached after a rapid transient. This transient is due to a dynamical reordering that occurs after the measuring ac current is applied and leads to a more mobile state.[12]

It is important to note that dissipation in the ZI_{ac}C W case is lower than in the I_{ac}C W one at low temperatures. This implies that an overall more ordered VS is obtained when cooling the sample in the presence of the ac current. As predicted in Ref. 12, we suspect that this is due to the inhomogeneous flow of the current that leads, in the ZI_{ac}C W case, to the reordering of the VS only close to the border of the sample where the highest currents flow. Another possible explanation is that the current inhibits the formation of a multiple domain (polycrystalline) VS when crossing the PE.

We turn now to our ac susceptibility results. We performed measurements in sample B[21] (dimensions 1 mm $\times$ 0.5 mm $\times$ 30 μm) using a conventional mutual inductance susceptometer at a frequency $f = 10.22$ kHz and ac magnetic field amplitude $h_{ac} = 2$ Oe applied in the c direction. This ac field is superimposed to a constant magnetic field $H_{dc} = 3$ kOe oriented as described above. The distribution of TB 's in crystal B is similar to that in crystal A (see inset in Fig. 1). The sample has a sharp zero field superconducting transition at 92 K and a transition width of 300 mK (10%-90% criterion) as determined with $h_{ac} = 1$ Oe.

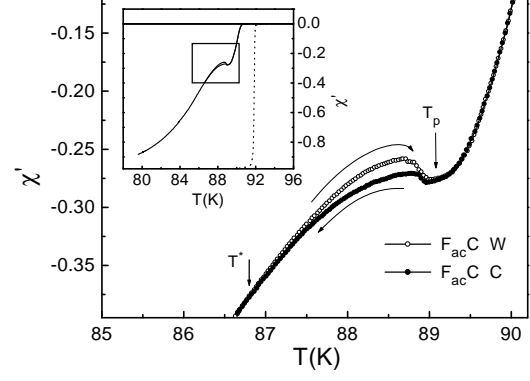Fig. 3 shows the real component of the ac susceptibility as a function of temperature, $\chi'(T)$. Temperature was varied as indicated by the arrows. The upper inset shows the superconducting zero field transition in dotted line and the $H_{dc} = 3$ kOe transition in full line. The dc field transition is enlarged in the main panel, where hysteretic response in observed. The lower curve corresponds to a field cool procedure. The dc and ac magnetic fields were applied in the normal state before cooling the sample. We refer to this case as F_{ac}C C. The curve F_{ac}C W was measured on warming immediately after measuring the F_{ac}C C curve. In the last case, the sample clearly presents lower shielding capability, $|\chi'|$, at intermediate temperatures, in accordance with the higher mobility that corresponds to a more ordered VS (compare with Fig. 1). The ac currents induced by the applied ac field seem to have the same effect on the VS as the ac transport currents, namely, they enable the vortex system to access to more mobile states. The PE is also observed with this technique, where the shielding capability increases anomalously with temperature and a dip in χ' appears before the VS melts.

In Fig. 4 we present ac susceptibility data that match our transport data of Fig. 2. In open symbols, we have plotted the F_{ac}C W data (of Fig. 3) as a reference. Solid symbols represent the warming curves that were measured immediately after cooling the sample down to different temperatures in zero applied ac field (ZF_{ac}C W). Note that the shielding capability in these warming curves is always larger than in the F_{ac}C C or F_{ac}C W procedures. As the system is cooled to different temperatures with no applied ac field, different responses are observed. At low temperatures, after a short transient
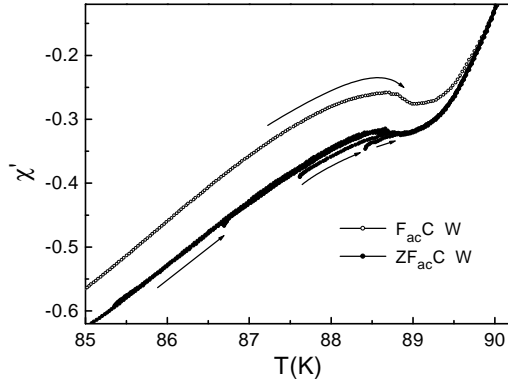
Fig. 4. S. O. Valenzuela

FIG. 4: $\chi'(T)$ measurements obtained on warming immediately after cooling to different temperatures in zero ac magnetic field, $ZF_{ac}C$ W (full symbols, sample B). Temperature was varied in the directions indicated by arrows. For comparison, it is shown the $F_{ac}C$ W in open symbols (see Fig. 3). $H_{dc} = 3$ kOe.

behavior, a response independent of the starting temperature is reached. As the starting temperature rises

and approaches T_p, the VS remains less mobile, the sample presents stronger shielding capability and the transient behavior does not lead to a common response. It is worth pointing out that performing equivalent analyses, we have drawn identical conclusions from the transport and ac susceptibility measurements.

To summarize, we have presented ac transport and ac susceptibility measurements in YBa$_2$Cu$_3$O$_7$ single crystals. We showed that the VS orders assisted by the motion induced by ac currents. The increase of elastic interactions against pinning at low temperatures leads to a crossover in the nature of the vortex motion that favors this reordering. This crossover from a plastic regime (which defines the characteristic motion of vortices at temperatures close to the peak effect) to an elastic regime at low temperatures would be responsible for the observed hysteresis between T^* and T_p.

* Present address: Physics Department, Harvard University, Cambridge, MA 02138.
[1] W. De Sorbo, Rev. Mod. Phys. **36**, 90 (1964).
[2] A.B. Pippard, Phil. Mag. **19**, 217 (1969).
[3] A.I. Larkin and Y.N. Ovchinnikov, J. Low. Temp. Phys. **34**, 409 (1979).
[4] R. Wördenweber, P.H. Kes, and C.C. Tsuei, Phys. Rev. B **33**, 3172 (1986).
[5] M.J. Higgins and S. Bhattacharya, Physica C **257**, 232 (1996) and Refs. there in.
[6] X.S. Ling and J.I. Budnick, in *Magnetic Susceptibility of Superconductors and Other Spin Systems*, edited by R. Hein *et al.* (Plenum Press, NY, 1991), pp. 377-388; W. K. Kwok, J.A. Fendrich, C.J. van der Beek and G.W. Crabtree, Phys. Rev. Lett. **73**, 2614 (1994); G. D'Anna, M.O. Andre and W. Benoit, Europhys. Lett. **25**, 225 (1994); J. Giapintzakis, R.L. Neiman, D.M. Ginsberg and M.A. Kirk, Phys. Rev. B **50**, 16001 (1994).
[7] M. Ziese, P. Esquinazi, A. Gupta and H.F. Braun, Phys. Rev. B **50**, 9491 (1994).
[8] A.I. Larkin, M.C. Marchetti and V.M. Vinokur Phys. Rev. Lett. **75**, 2992 (1995).
[9] W. Henderson, E. Y. Andrei, M.J. Higgins and S. Bhattacharya, Phys. Rev. Lett. **77**, 2077 (1996); N.R. Dilley, J. Herrmann, S.H. Han and M.B. Maple, Phys. Rev. B **56**, 2379 (1997); G. Ravikumar, V. C. Sahni, P.K. Mishra, T.V. Chandrasekhar Rao, S.S. Banerjee, A.K. Grover, S. Ramakrishnan, S. Bhattacharya and M.J. Higgins, Phys. Rev. B **57**, R11069 (1998); W. Henderson, E.Y. Andrei and M.J. Higgins, Phys. Rev. Lett. **81**, 2352 (1998); X.S. Ling, J.E. Berger and D.E. Prober, Phys. Rev. B **57**, R3249 (1998); Z.L. Xiao, E.Y. Andrei and M.J. Higgins, Phys. Rev. Lett. **83**, 1664 (1999).
[10] For earlier work see H. Küpfer and W. Gey, Phil. Mag. **36**, 859 (1977) and Refs. there in.
[11] T. Ishida, K. Okuda, H. Asaoka, Y. Kazumata, K. Noda and H. Takei, J. Low. Temp. Phys. **105**, 1171 (1996); B. Sas, F. Portier, K. Vad, B. Keszei, L.F. Kiss, N. Hegman, I. Puha, S. Mszros and F.I.B. Williams, Phys. Rev. B **61**, 9118 (2000); D. Pal, D. Dasgupta, B.K. Sarma, S. Bhattacharya, S. Ramakrishnan and A.K. Grover, Phys. Rev. B **62**, 6699 (2000).
[12] S.O. Valenzuela and V. Bekeris, Phys. Rev. Lett. **84**, 4200 (2000).
[13] S.O. Valenzuela and V. Bekeris, Phys. Rev. Lett. **86**, 504 (2001).
[14] P. Thorel, R. Kahn, Y. Simon and D. Cribier, J. Phys. (Paris) **34**, 447 (1973); X.S. Ling, S.R. Park, B.A. McClain, S.M. Choi, D.C. Dender and J.W. Lynn, Phys. Rev. Lett. **86**, 712 (2001); H. Safar *et al.* (unpublished).
[15] A. Brass, H.J. Jensen, and A.J. Berlinsky Phys. Rev. B **39**, 102 (1989); A.E. Koshelev, Physica C **198**, 371 (1992).
[16] F. de la Cruz, D. López and G. Nieva, Phil. Mag. B **70**, 773 (1994).
[17] D.R. Nelson and V.M. Vinokur, Phys. Rev. B **48**, 13060 (1993).
[18] B. Maiorov, G. Nieva and E. Osquiguil, Phys. Rev. B **61**, 12427 (2000).
[19] H. Safar, P.L. Gammel, D.A. Huse, D.J. Bishop, J.P. Rice and D.M. Ginsberg, Phys. Rev. Lett. **69**, 824 (1992); W.K. Kwok, S. Fleshler, U. Welp, V.M. Vinokur, J. Downey, G.W. Crabtree and M.M. Miller, Phys. Rev. Lett. **69**, 3370 (1992).
[20] Intermediate levels of dissipation have been observed for fast cooling or warming procedures, where the small number of applied ac cycles per temperature interval partially

reorder the VS.[12,13]

[21] I.V. Aleksandrov, A.B. Bykov, I.P. Zibrov, I.N. Makarenko, O.K. Mel'nikov, V.N. Molchanov, L.A. Muradyan, D.V. Nikiforov, L.E. Svistov, V.I. Simonov, S.M. Chigishov, A.Ya. Shapiro and S.M. Stishov, JETP Lett. **48**, 493 (1988).